SWEDEN UNDERGROUND
- Rock Engineering and How It Benefits Society

Preview of selected contence

SWEDEN UNDERGROUND

Rock Engineering and How It Benefits Society

BeFo
STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

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Swedish Rock Engineering Association

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TRAFIKVERKET
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Preface

Competition for buildable land, not least in the centres of towns and cities, is intensifying. Experience has shown that many important functions in dense city centres can be placed in tunnels and rock caverns instead of building them on the surface. One common feature of underground facilities is that there is often little or no sign of them on the surface, thereby freeing up valuable land for other purposes such as buildings and parks.

The option of building underground applies not only to infrastructure, such as road and rail tunnels and wastewater treatment plants, but also facilities for other human activities and recreation, such as underground museums, cinemas, swimming pools and archives. These and many more examples of how the underground space can be used to benefit society are described in this book.

In an international perspective, Sweden holds a leading position in underground construction, with extensive experience of different types of project. The country has great expertise in rock engineering and a cutting-edge manufacturing industry that serves the sector, and conducts world-leading research. The book contains many examples.

One important target group is planners and decision-makers who wish to learn more about the subject and discover the potential of underground construction. However, the text has been deliberately pitched at a level to make the content easily accessible and comprehensible for a broad audience, not just for specialists.

The book is divided into six chapters as follows:

Chapter 1 describes common motives for placing facilities in tunnels and rock caverns, and the favourable geological conditions for underground construction in Sweden.

Chapter 2 considers planning issues and legal aspects of underground construction.

Chapter 3 describes technological aspects of rock construction.

Chapter 4 contains descriptions of over 30 rock facilities in Sweden, including why and how they were built. Most are in operation, but some of the projects are still in the planning stage.

Chapter 5 presents the latest research and development in rock engineering, conducted at leading universities and research institutes in Sweden.

Chapter 6 looks to the future, and describes some conceivable underground projects in Sweden. Some have even reached the planning stage, while others are more visionary in character.

The book is the result of a collaboration between the Rock Engineering Research Foundation (BeFo), the Swedish Rock Engineering Association, the Swedish Transport Administration (Trafikverket), the Swedish Nuclear Fuel and Waste Management Company (SKB), the J. Gust. Richert Memorial Foundation, and professionals who contributed on a volunteer basis.

Our hope is that the book will increase understanding of the potential of tunnels and rock caverns in resolving societal challenges, and of how the rock under our feet can be a valuable resource in urban construction.

Stockholm, March 2018

Per Tengborg
Rock Engineering Research Foundation - BeFo

Robert Sturk
Swedish Rock Engineering Association


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THE UNDERGROUND RESOURCE

In Sweden, tunnels and rock caverns are used for a wide range of purposes. Because the facilities are underground, and therefore largely out of sight for the general public, this aspect of urban planning is generally less well known to most people. This introductory chapter examines the advantages afforded by building underground, and the favourable geological conditions in Sweden that make this possible. Some aspects of size and cost, as well as how people perceive the underground experience, are also considered.

The Northern Link tunnel at the Roslagstull junction in Stockholm. Photo: Swedish Transport Administration.

Most underground facilities in Sweden have been built under the largest cities, but are also found in smaller towns and in rural areas. Most concern infrastructure of various types, such as the metro system in Stockholm, road and rail tunnels, wastewater tunnels, and rock caverns containing wastewater treatment plants or district heating production facilities. However, the underground resource is now also being used in other ways, for facilities such as museums, archives, data centres and car parks.

One positive feature of underground facilities is that they have relatively limited impact on the environment at surface level, both during construction and in operation. Even if the costs of building underground can be relatively high, such solutions offer advantages that may outweigh the cost aspect. These include freeing surface land for other purposes, operational benefits, and reducing environmental impact.

Sustainable development is vital to the future of society, and subsurface development can play a very important role.

WHY BUILD UNDERGROUND?

Chapter 4 contains descriptions of a selection of rock engineering projects in Sweden. In most cases, a combination of factors lay behind the decision to build underground, and the following is a brief review of the most common reasons.

Facilities can be built in attractive, central locations

Land is at a premium in the centres of large cities. By moving certain functions into tunnels and rock caverns, and into cuttings and rock cavities that are then covered, this retains a central location while creating space for other activities in attractive areas on the surface.

An underground central location may be more advantageous than a surface facility in a more peripheral location. This was one of the reasons why Bahnhof decided to build a data centre in a former underground shelter in central Stockholm. Another example is the National Library of Sweden, where room was created for a large book storage by blasting two rock caverns immediately under the main building, rather than building on a completely separate site.

Other examples are the Bergakungen cinema complex in Gothenburg and the Johannes emergency and rescue centre in Stockholm.

Frees up land for other uses

When roads are placed in tunnels, or built in cuttings and covered, extensive areas of land can be freed up and scars in the landscape healed. Space for building may be created in highly valuable locations that more than cover the cost of moving a facility down into the rock.

One example is the construction of the Göta Tunnel in Gothenburg. Moving a motorway underground released land in the inner city for building, and the land previously occupied by the road became attractive residential and commercial areas near the harbour. The motorway tunnels in Stockholm have had a similar effect.

Construction of underground car parks in Stockholm, such as Stigsbergsgaraget, has reduced the amount of space taken up by parked cars, enabling the land to be used for other purposes.

Stigbergsgaraget in Stockholm is an underground car park that relieves pressure on surrounding streets. The car park contains 300 spaces, equivalent to 2-3 km of roadside parking. Photo: Torbjörn Winqvist.

Potential for expansion

Surface structures, particularly in densely built city centres, have very limited space for expansion, but this does not apply to the same extent for underground facilities. Many underground facilities can relatively easily be expanded by, for example, building a new rock cavern beside the original one or extending a tunnel system. Capacity at the Henriksdal Wastewater Treatment Plant has been expanded several times by building more treatment basins in rock caverns under a densely built part of Stockholm.

Similarly, tunnels are often built larger than is initially necessary, to allow for future needs. Tunnels for technical utility supply, such as those at Södersjukhuset hospital in Stockholm, can be built with plenty of space for future pipes or cables, at no or very little extra cost.

The underground book storage at the National Library of Sweden is in a pair of rock caverns so large that the library will be able to expand into it gradually over 40 years.

Enable important communication routes

Routing new major roads and railways through city centres is only possible underground – there is no alternative. The route can be adjusted both vertically and laterally to local conditions. An example of a new route is the City Tunnel in Malmö, which was built under the centre of the city from the Central Station, originally a terminus, towards the Öresund Bridge, which increased capacity for rail traffic throughout the region. The urban motorways and new railways in tunnels under the centres of Stockholm and Gothenburg are other examples.

Overcome topographical challenges

Building roads, railways, and pipe and cable systems in undulating terrain is complicated and expensive. By placing, for example, railways in tunnels, the tracks can be built with very gentle gradients and large curve radii, which improve the capacity of the line, as in the Hallandsås Tunnel and the new rail tunnels in Norrland.

Underground wastewater tunnels can be built in straight sections, transporting water long distances with a natural fall if built with a constant gradient – 0.1% is sufficient. An example is the 20-km Bromma Tunnel, which will lead wastewater under residential areas and a lake to a wastewater treatment plant.

Artistic decoration at Odenplan Station, City Line.
Photo: Swedish Transport Administration.
Photographer: Mikael Ullén.

Out of sight, out of mind

Surface facilities that generate noise and/or odour and cause other environmental disturbances cannot be built close to residential areas, and a sizeable buffer zone is needed. However, when such facilities are built in rock caverns, they become invisible to the surroundings, and any odour can be treated. The facilities can then be built in the rock close to built-up areas, and the need to acquire land is considerably reduced.

The Käppala Wastewater Treatment Plant could be built under a residential area, adjacent to the most suitable site for discharge of treated water. All the treatment basins are placed in rock caverns, and odours generated by the enclosed treatment processes are emitted via a 150-m chimney. Norsborg Metro Depot was also built under a residential area with little impact on the surroundings.

New uses for disused tunnels, rock caverns and mines

Many of today's underground facilities have been converted from older premises, and are now used in different ways. Some were originally built as defence facilities that have since been decommissioned and made available for civilian use. An example is The Skeppsholmen Caverns in Stockholm, where the Museums of World Culture arrange exhibitions in rock caverns previously used by the Swedish Navy. The Aeroseum aviation history museum near Gothenburg has taken over former underground air hangars, and the Pionen data centre in Stockholm was built in a former bomb shelter.

Disused mines and quarries have been given a new lease of life. A limestone quarry in Dalarna has been converted into the Dalhalla concert venue, and a limestone mine near Örebro is now a logistics and test centre.

High levels of security and protection

An underground location is often chosen to provide a high level of security against risks such as break-in, impact, fire and accidents. For example, security was the most important motive for building the Pionen data centre in a centrally located rock cavern, originally used by the Swedish Defence, and security was also an issue in the decision to build the Norsborg Metro Depot underground.

A location in rock also protects and insulates the surrounding environment from activities that may entail

A large cinema complex could be built in central Gothenburg by placing it in a blasted rock cavity. This enabled the building to blend in with the existing city centre environment.
Photo: Bert Leandersson.

risks. Examples are the Skallen natural gas storage near Halmstad, the nuclear waste repositories near Oskarshamn and Forsmark, and the mercury-bearing waste storage at Rönnskär near Skellefteå.

Energy advantages

Rock caverns are characterised by very stable temperatures, and the surrounding rock provides heat insulation. These properties contribute to low running costs. For example, the logistics centre in Kvarntorp, located inside a former mine, has very low costs for heating and ventilation, and the National Library book storage has a naturally stable indoor climate. The Hornsberg energy storage facility provides cold water inflow to the district cooling system in Stockholm.

Low maintenance needs and operational advantages

Rock caverns are stable structures, with low maintenance needs. In terms of processes, it is simpler to run, for example, a wastewater treatment plant underground in rock than outdoors, with good lighting and ventilation providing a pleasant working environment and where the equipment is always dry and warm.

Rock properties can be utilised

The rock itself has certain properties that benefit underground facilities. For example, the ability to withstand great pressure was one of the factors behind the decision to build the Skallen natural gas storage in a rock cavern. Because of the strength of the rock, the gas could be stored at high pressure. In storage of hazardous waste, the rock provides natural insulation. In underground wastewater treatment plants, such as Henriksdal and Käppala in Stockholm, the treatment basins could be built in rock and could be made deeper than would be economically viable in concrete. As a result, the physical size of the facility could be kept down.

FAVOURABLE GEOLOGICAL CONDITIONS

The many advantages afforded by building underground are of little worth if the geological conditions are not favourable. Fortunately, the rock underlying much of Sweden is highly suitable for building tunnels and rock caverns.

Much of the country lies on a very hard basement of Precambrian Shield rocks, which either form the surface or are covered by a thin layer of soil. The basement mainly comprises granitoid and metamorphosed rocks, transformed

Aeration basins for biological treatment of wastewater with the activated sludge process.
Left: basin in operation. Right: basin emptied for inspection. Photos: ©Kari Kohvakka, Stockholm Vatten och Avfall.

crystalline rock types that contain varying degrees of fractures and crushed zones. The solid rock is generally very strong, but permeability in the fractures and crushed zones can vary considerably, affecting the conditions for rock construction.

In some parts of the country, the crystalline basement is overlain by sedimentary rocks, mainly sandstones, limestones and shales. The sedimentary rocks differ from the crystalline basement in two main ways. One is that the strength of the individual rock types varies, from very strong to very weak. The other is the layered nature of the rocks. Often, the solid sedimentary rock types are more porous, which can have a negative effect on deformation and permeability properties.

Choosing a location for an underground facility

Every area where an underground facility is under consideration has its own geological history that determines the rock properties and its fracture system. In order to decide whether construction of a facility is viable, it is important to understand the geological history, so that issues such as mechanical stability, permeability, effect on the surrounding area, and maintenance aspects can be considered.

Rock is not homogeneous, and sections of good-quality rock may also contain zones with different rock types of poorer quality that present problems for rock engineers. Extra reinforcement measures, drainage or sealing may be needed, which increase building costs.

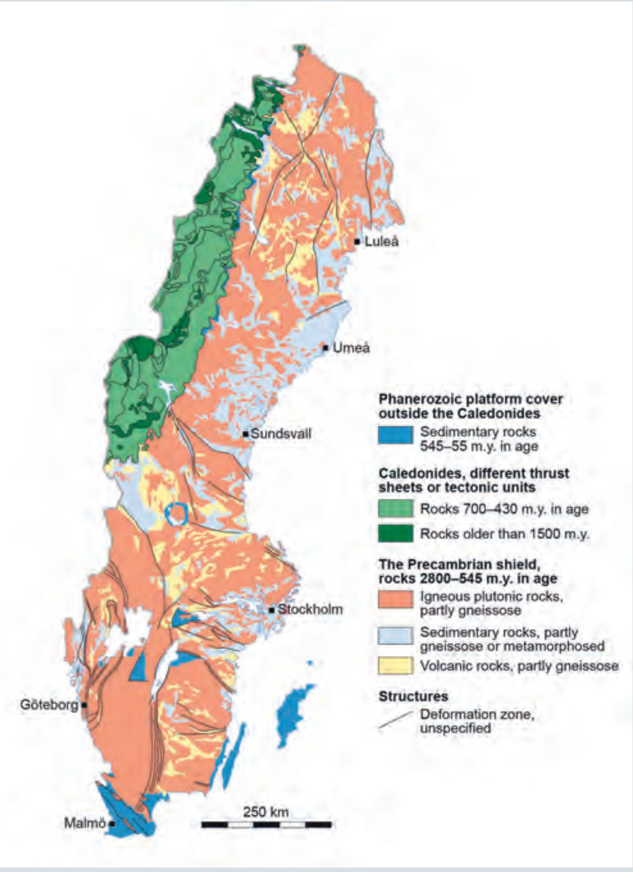
In the preliminary assessments, geologists and rock engineers consider the planned facility in relation to the geological conditions, determining the best site or route, and avoiding problematical sections and undesirable effect on the surroundings. The most suitable construction technique is identified in this phase. Here, geologists and engineers use geological maps, databases, and existing comprehensive documentation about local rock conditions generated by earlier facilities in the vicinity, drilled wells, etc. More comprehensive investigation measures, including geophysical methods, improve the reliability of the preliminary assessments.

When a more detailed analysis is necessary, there are a number of different methods available to find out more about the rock properties and constructability. These are described in more detail in Chapter 3.

GEOLOGY OF SWEDEN IN BRIEF

The rock in Sweden comprises three main units: the Precambrian crystalline basement, the remains of a sedimentary rock cover, and the rocks in the Scandinavian Caledonides mountain range.

- The basement is part of a palaeocontinent, Baltica, and comprises rocks formed during the Precambrian eras approximately 2800-545 million years ago.
- Most of the sedimentary rocks overlying the basement to the east of the mountain range were formed in the period from the Cambrian and into the Tertiary period 545-55 million years ago. The sedimentary rocks are fossil-bearing and overlie the crystalline basement.
- The Scandinavian Caledonides are the remains of an old mountain range formed 510-400 million years ago when Baltica collided with Laurentia (North America-Greenland). Super-regional thrusts forced up older rocks from the west to form a long mountain range.



In Sweden, the bedrock is dominated by crystalline rock types such as granite and gneiss. In some areas, the crystalline basement is overlain by sedimentary rock types, including limestone, shown in dark blue on the map. Map: ©Geological Survey of Sweden (SGU).

The crystalline basement

Most of the rocks in Sweden are crystalline, which means that the minerals in the rock crystallised at different rates in various geological processes, mainly due to high pressures and temperatures. This explains why rocks vary in terms of hardness and fracture systems.

The basement is fractured for several reasons. During a relatively slow cooling process, different parts of the rock solidified at different rates, causing zones of weakness and shrinkage fractures. Another reason can be linked to the mountain-building phases caused by forces in continental drift and plate tectonics, which cause horizontal stress fields in the crust. A third reason for fracturing is the relief of downward pressure, as overlying rock layers are removed by erosion. Continental ice sheets also contributed to fracturing, first by exerting downward pressure and then by that pressure being relieved when the ice melted. Fractures were also caused by induced shearing on the rock surface, permafrost and changes in groundwater pressure.

Sedimentary rocks

In some parts of Sweden, the crystalline basement is still covered by younger, sedimentary rocks, but in the rest of the country these layers have been eroded away. Sedimentary rocks are found in Skåne, on the islands of Öland and Gotland, the Östgöta and Närke Plains, the Västgöta plateaus, in the area around Siljan in Dalarna, and along the edge of the mountain range to the west.

Sedimentary rocks are formed when fine particles are compacted and cemented to form solid rock. The composition can vary greatly, depending on the origin of the constituent parts and the marine environment in which they were formed. Sand and gravel can, for example, have been transported to a sedimentation area in the sea, where they compacted and solidified to form a sandstone. Limestone is generally formed by deposition of calcium sludge and shells from various crustaceans. Shale is a hard sedimentary rock with a high clay content. As with the rocks in the crystalline basement, sedimentary rocks can also contain secondary structures such as fractures, faults and folds.

The photo illustrates a problem that rock engineers may encounter when planning a rock facility. Here, the rock has been displaced approximately 2.5 m laterally along a vertical fracture zone. Photo: Thomas Eliasson, Geological Survey of Sweden (SGU).

SIZE AND SHAPE OF UNDERGROUND FACILITIES

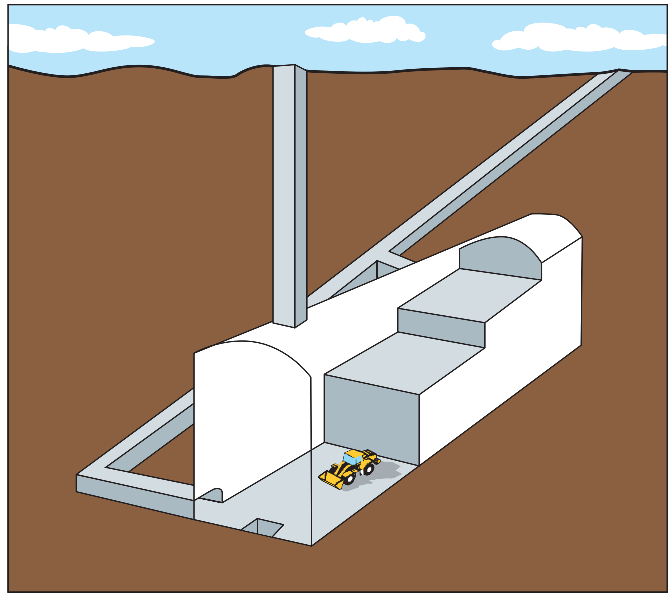
One unique property of underground structures is the comparative freedom with regard to geometric shape: long tunnels can be built in any direction, and rock caverns can be made large, wide, deep or merged with other caverns. Restrictions that apply on the surface, and that determine what can be built there, do not apply underground. Purpose-built rock caverns have incomparable advantages.

Some rock caverns in Sweden are 30-35 m wide, and in Norway, an underground sports hall has been built that is 60 m wide, indicating potential to build wider rock caverns than those built so far.

Construction technology sets the conditions for what is most economically advantageous to build. Where a large cross-sectional area is desirable, it may be more viable to keep the width below 25 m and instead increase the height. This is because the roof section is the most expensive part to build, while bench blasting of the walls and floor is relatively cheap.

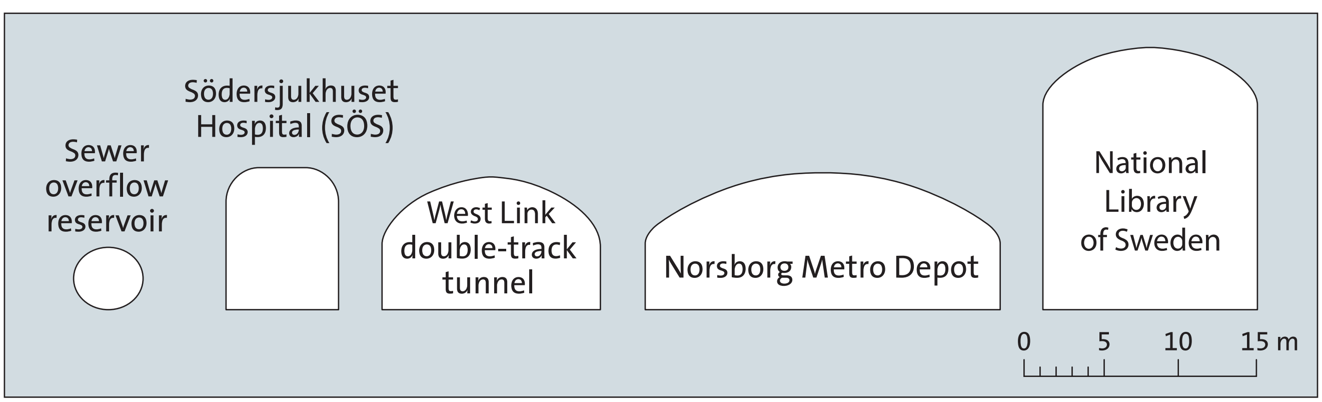
Rock caverns can be long. An oil storage facility at Lysekil north of Gothenburg comprises six parallel rock caverns totalling 4330 m, of which the longest is 850 m.

Tunnels built with the drill-and-blast method need to be at least 2.5 m wide to ensure sufficient space for the machines. A minimum roof height of 4 m is needed to ensure sufficient space for ventilation pipes above the machines. The smallest cross-sectional area is therefore 8-15 m^2, depending on the type of machine used. Smaller tunnels can be built with machines on rails, but they are not cheaper per metre of tunnel.



Large rock caverns are built in stages. First, a tunnel is blasted and the roof secured. The floor is then deepened in one or more stages using bench blasting, which is simpler and cheaper. A connecting tunnel provides access to the cavern at various levels, so that blasting and removal of excavated rock can be carried out as efficiently as possible. Illustration: Ulf Lindblom.

Tunnels built with boring machines have a circular shape and can have larger cross sections. Horizontal tunnels are excavated with tunnel boring machines (TBM), and the desired diameter determines the size of machine. The world's largest TBM is nearly 18 m in diameter, and the maximum size is constantly increasing. The Hallandsås Tunnel, built with a TBM, has a diameter of 10.6 m. Vertical holes can be excavated with the raise boring method, forming shafts with smaller diameters.



Cross-sections of underground facilities drawn at the same scale. Sewer overflow 9.5 m^2, SÖS utility tunnel 30 m^2, West Link double-track rail tunnel 90 m^2, Norsborg Metro Depot 155 m^2, National library 275 m^2. The largest cross-sectional area of facilities commonly built in Sweden is 600 m^2 (oil storage caverns). Illustration: Torbjörn Winqvist.

Tunnels can be long. The longest tunnel in Sweden is the Bolmen Tunnel, over 80 km long and built in rock. The tunnel delivers drinking water to cities in southern Skåne.

Underground train stations and other public underground facilities need to be close to and connect to surface structures. With modern technology, the vertical distance to the surface and other facilities may be as little as 2-3 metres. The actual height of the rock cover depends on geological conditions and tunnel/cavern span.

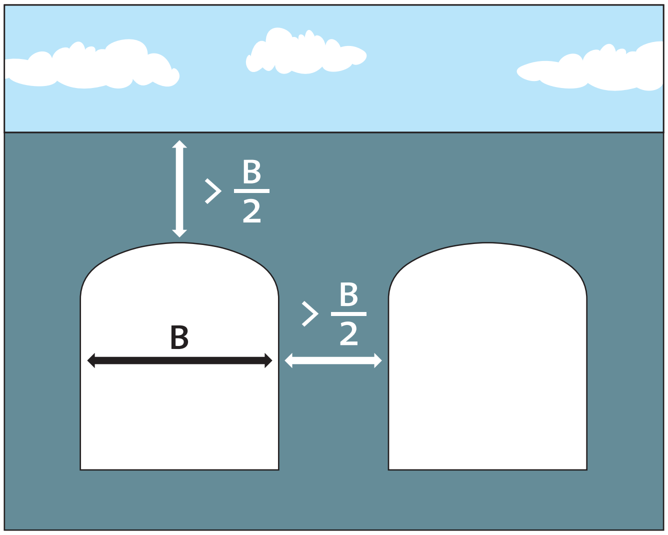


Diagram showing roughly how much rock is needed above the roof and between two tunnels. The dimensions shown are intended to give the reader a general impression only, and must be determined more accurately in relation to the local geology. Where conditions are favourable, the relative dimensions shown can be reduced, for example where it is desirable to build public facilities close to the surface. Illustration: Torbjörn Winqvist.

A drilling rig in operation. Four holes are drilled simultaneously, and a computer controls the orientation and depth of the holes. Photo: Epiroc (formerly Atlas Copco).

Sketch showing possible future appearance of part of Gothenburg Central Station on the West Link. An important design feature is to allow daylight to penetrate to the interim level. Illustration: White arkitekter.

In the tunnels containing Stockholm's urban motorways, clear signs and overhead lighting are major priorities. Artistic decorations at the junctions help motorists orientate themselves. Photo: Mikael Ullén.

Artistic decoration at Odenplan Station. 'Oden's Garden' by Mari Rantenen. Photo: Swedish Transport Administration, Citybanan. Photographer: Hans Ekestang.

Dalhalla outdoor music venue. Photo: Dalhalla.

UNDERGROUND FACILITIES AND URBAN PLANNING

Finding space for new or changed needs has become a major challenge in the densely-built city. Building facilities underground offers interesting alternatives, but tunnels and rock caverns have unique characteristics that the planner must be aware of. This chapter examines aspects of municipal and regional planning relevant to underground construction projects, and presents an overview of the applicable legislative framework.

Image: Shutterstock

PROJECT DESIGN AND CONSTRUCTION

This chapter focuses on activities in the various phases of an underground construction project, from feasibility study to design, construction and operation. The most commonly used investigation methods are described, as well as the technology and techniques involved in the construction phase. Risks and uncertainties, the effect of a construction project on the surroundings, and some important aspects relating to maintenance and inspections of facilities in the operational phase, are also considered.

Excavation site, City Line, Stockholm. Photo: Swedish Transport Administration, City Line Project. Photographer: Mikael Ullén.

BACKGROUND

Rock engineering technology has its origins in the mining industry but, over time, methods, equipment and materials have been adapted to meet other societal needs. Civilian and military underground construction, particularly in cities, grew in the 1940s and 1950s, so manufacturers adapted their product development to the needs of this market.

Rock construction has developed into a comprehensive industrial process, and a strong domestic manufacturing sector has played an important role in this development. Major companies such as Epiroc (formerly Atlas Copco), Sandvik, Nitro Nobel and Volvo have developed drills, drill bars and rods with sophisticated cemented carbide cutting tools, blasting equipment, machines for rock reinforcement, and transport equipment for loading and removing rock spoil.

Underground facilities serving society

UNDERGROUND SOLUTIONS TO SOCIETAL CHALLENGES

There is a rich diversity of underground facilities in Sweden, with varying size and function, built to meet a variety of needs. Infrastructure projects are the most common type, including road and rail tunnels, car parks, and wastewater treatment plants. Storage is another major function, and rock caverns house petroleum and biofuel products, hazardous waste… and even books. Concert halls, museums and cinemas have been built in rock, and many disused underground facilities have been brought back to life with new functions.

In this chapter, we present a selection of projects in Sweden that illustrate the broad range of functions for which underground rock engineering can provide solutions. Most of the facilities have been in operation for some time, while others are under construction. The descriptions include why and how the facilities were built and what lay behind the decision to build them underground.

Photo: Swedish Transport Administration. Photograper: Mikael Ullén.

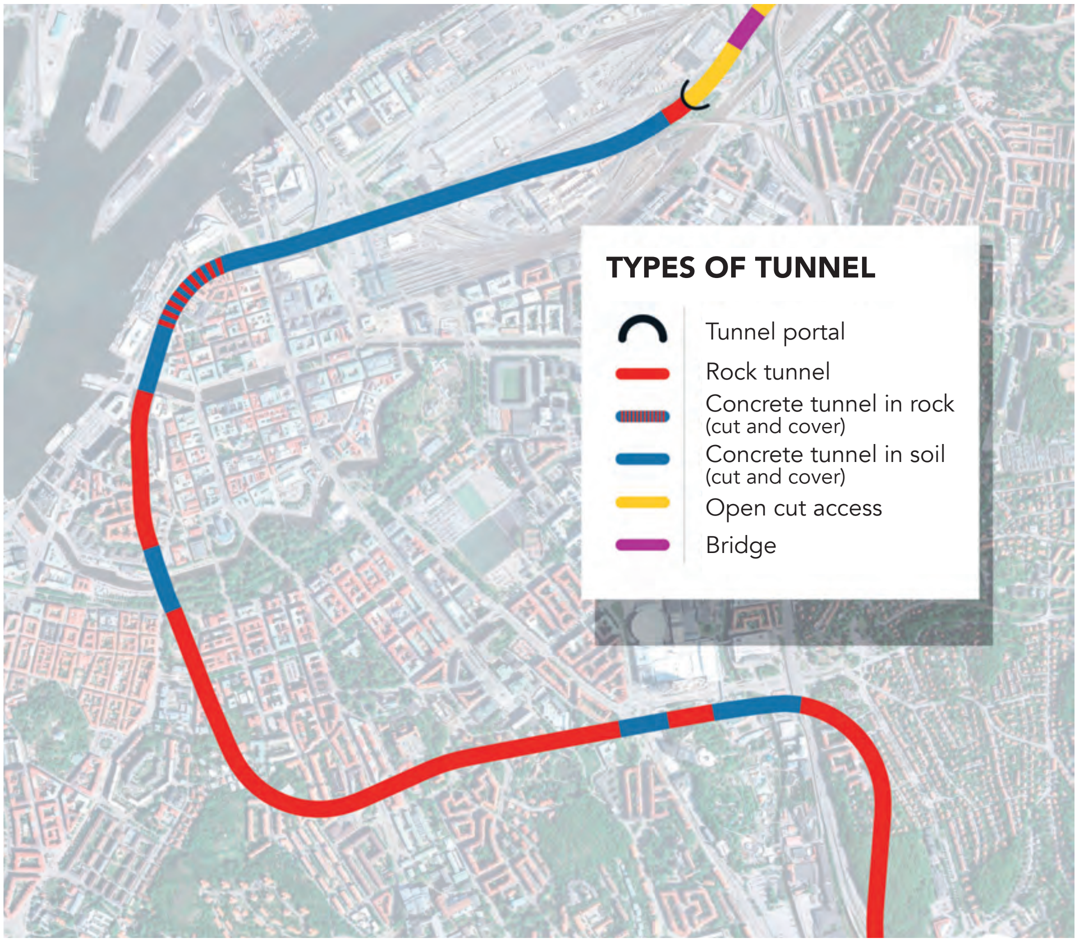


Illustration: Swedish Transport Administration.

West Link and Korsvägen Station

Improving rail links and access in central Gothenburg

The railway system in the Gothenburg region has reached maximum capacity, which is hindering regional development. To overcome these problems, a new line, the West Link, is to be built for through traffic, commuter traffic and regional trains. Much of the line will run in tunnels under the city centre, and three underground stations will be built, one of which is Korsvägen.

National Library of Sweden

Rock caverns solve book storage problems

Photo: Istvan Borbas, National Library of Sweden.

Photo: Ulf Lundin, National Library of Sweden.

TIME OF CONSTRUCTION	1992-1993
EXCAVATED ROCK VOLUME (m^3)	150,000
OWNER	National Library of Sweden and the National Property Board of Sweden
MAIN DESIGNER	Tyréns
MAIN CONTRACTOR	NCC

The National Library of Sweden (Kungliga Biblioteket, KB) is situated in Humlegården Park in Stockholm. The library collects and stores all printed material published in Sweden since 1661, and now also audio-visual media. The library needed to expand to increase storage capacity, and the solution was to build a cavern in the rock underneath the main building.

Stigbergsgaraget

Car park built in rock reduces street parking problem

Photo: Torbjörn Winqvist.

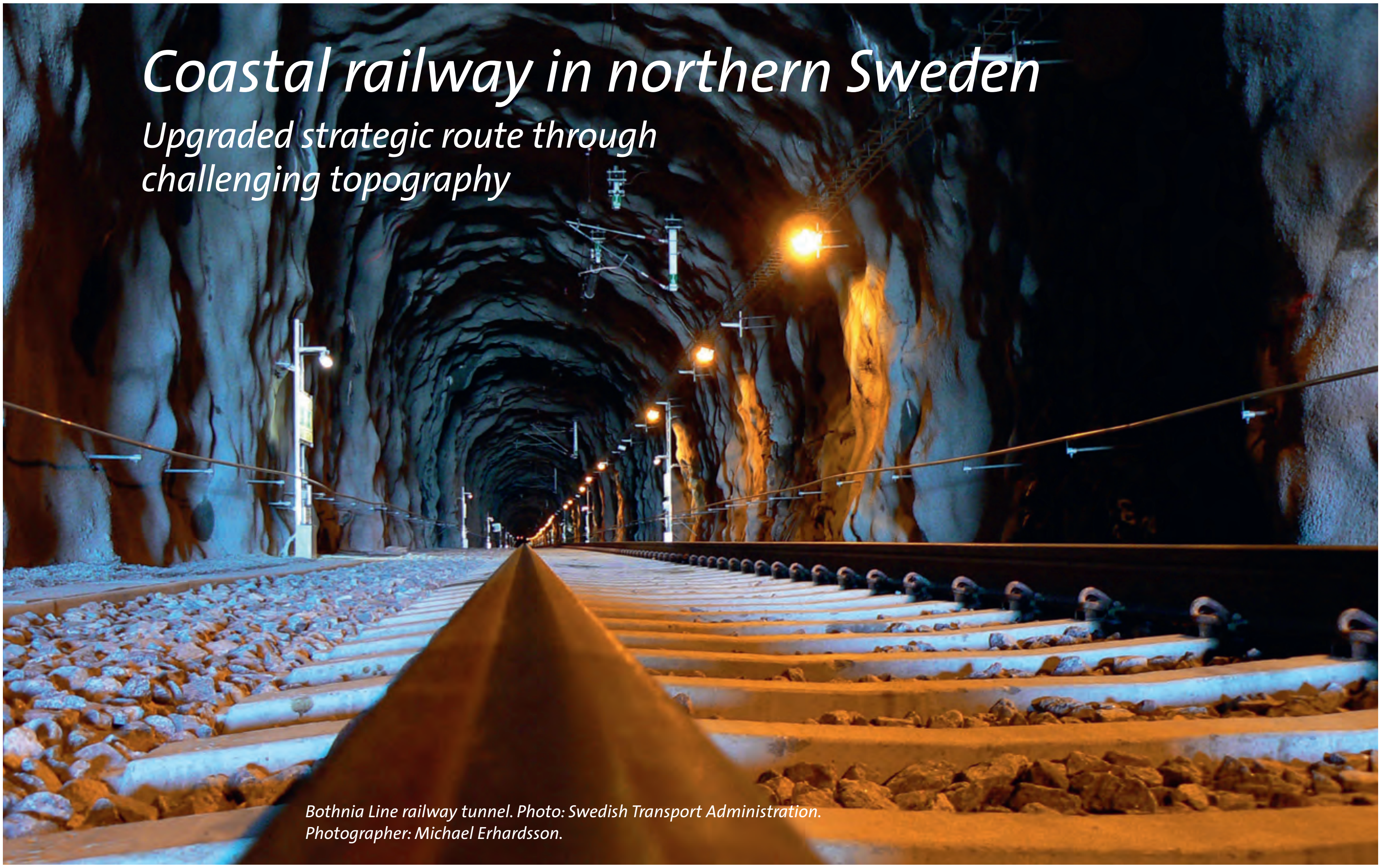
Photo: Stockholm Parkering.

TIME OF CONSTRUCTION	2013-2015
PROJECT COST (SEK million)	140
EXCAVATED ROCK VOLUME (m^3)	approx. 38,000
OWNER	Stockholm Parkering
PROJECT MANAGER	Stockholm Parkering
MAIN DESIGNER	WSP
MAIN CONTRACTOR	Veidekke

Two-thirds of households in Stockholm have access to a car, and around 15 percent of road surfaces are used for parking. Space is at a premium in the city, so there is a strong case for replacing roadside parking with underground car parks. One example is Stigbergsgaraget – an open, bright three-storey car park built entirely in rock. The project was planned and designed within a very short time, thanks to the use of an innovative working method, and was nominated for the Building of the Year Prize in 2015.

Coastal railway in northern Sweden

Upgraded strategic route through challenging topography



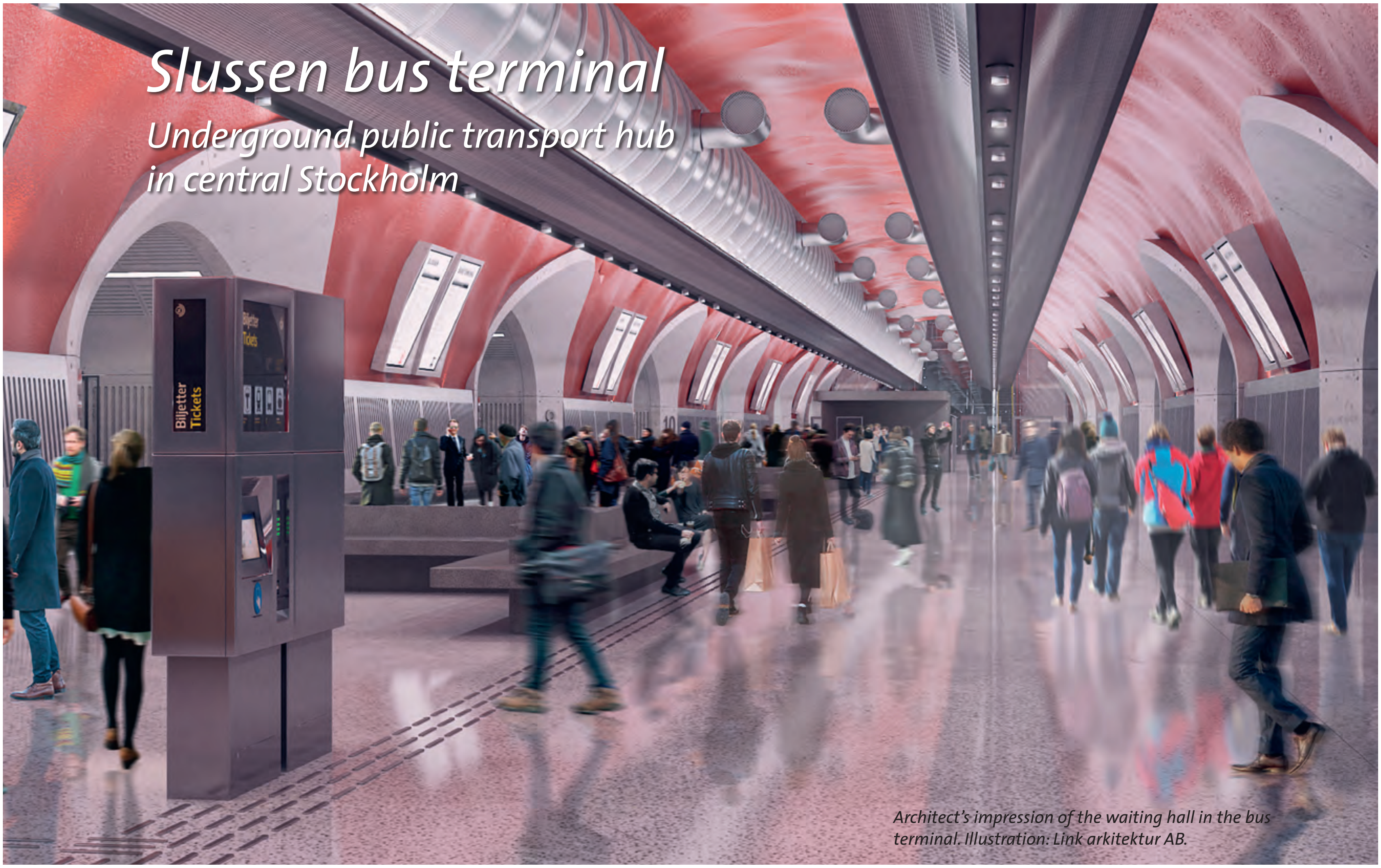
Bothnia Line railway tunnel. Photo: Swedish Transport Administration. Photographer: Michael Erhardsson.

TIME OF CONSTRUCTION	2007-2012
PROJECT COST (SEK million)	Ådal Line: 6600 (2010) Bothnia Line: 15,000 (2010) North Bothnia Line: estimated 27,000 (2013)
TOTAL TUNNEL LENGTH	Ådal Line 11 km, Bothnia Line 25 km, North Bothnia Line (planning stage, 2017)
OWNER	Swedish Transport Administration
PROJECT MANAGER	Various
MAIN DESIGNER	Various
MAIN CONTRACTOR	Various

The coastal railway in northern Sweden is part of a corridor of railway lines along the Gulf of Bothnia that will link Stockholm and Helsinki. This strategic corridor includes an existing system of lines linking Stockholm and Umeå. The North Bothnia line between Umeå and Luleå is in the planning stage, and the final section will run from Luleå to Boden and then on to Haparanda on the Sweden/Finland border. The coastal railway is a major engineering project requiring many tunnels and bridges to create a route with the capacity for heavy goods trains and fast passenger trains.

Slussen bus terminal

Underground public transport hub in central Stockholm



Architect's impression of the waiting hall in the bus terminal. Illustration: Link arkitektur AB.

Slussen has been a major transport hub in central Stockholm since the 1930s, but the area is now being redeveloped to meet current and future needs for modern traffic solutions. The major project includes a new bus terminal, but available land along the waterfront is very limited. The solution is to rebuild the entire terminal in the rock under Katarinaberget.

Hallandsås Tunnel

Complex project increases capacity on the West Coast Line

Photo: Skanska.

TIME OF CONSTRUCTION	1993-2015
PROJECT COST (SEK million)	10,500
EXCAVATED ROCK VOLUME (m^3)	Approx. 1,500,000
OWNER	Swedish Transport Administration
PROJECT MANAGER	Swedish Transport Administration
MAIN DESIGNER	Skanska-Vinci HB
MAIN CONTRACTORS	Skanska-Vinci HB

The route of the West Coast Line railway over the Hallandsås Ridge had been a bottleneck for nearly a century. The solution was to build a tunnel through the ridge, but the project encountered major problems and proved to be a major challenge for Swedish rock construction engineers.

Årsta tunnels

Holding reservoirs in rock solve stormwater overflow problem

By rebuilding the existing tunnels and blasting operational areas for sediment removal, stormwater treatment goals have been reached. Photo: Stefan Tyrbo.

TIME OF CONSTRUCTION	2006-2007
PROJECT COST (SEK million)	60
EXCAVATED ROCK VOLUME (m^3)	15,500 and 12,000
OWNER	Stockholm Vatten och Avfall
PROJECT MANAGER	Sweco
MAIN DESIGNER	WSP Sverige AB
MAIN CONTRACTOR	ODEN

Approximately 60% of the land surface around the Årstaviken inlet in Lake Mälaren, comprises hard artificial surfaces. The water in the inlet contained high levels of phosphorus, nitrogen and bacteria because stormwater mixed with untreated wastewater during periods of heavy rain. The situation became so acute that bathing was prohibited in the 1990s. A rock engineering project has helped alleviate the problem.

Dalhalla, a rock amphitheatre

Disused quarry now a magnificent outdoor music venue

Photo: Dalhalla.

"It's no wonder I'd never come across the quarry before – it's so well-hidden in the forest. When I did find it, I clambered down as far as I could, sang Tosca's prayer, and did some vocal exercises. The acoustics were absolutely incredible. I knew straight away I'd found what we were looking for, and I knew exactly what I wanted to do with this place."

Rättvik municipality had been looking for a suitable site for summer festivals, and it was the former opera singer Margareta Dellefors who discovered the perfect place in 1991 – a disused limestone quarry deep in the forest just outside the town. She immediately saw the potential of the quarry for use as a music arena. The location was ideal, far away from all buildings, and well-shielded against noise pollution from roads and industry.

She was appointed project manager for the entertainment programme. The project was supported by Rättvik municipality and Dalarna County Council. In June 1993, a test concert was held with an invited audience, press and TV, and later the same year the Dalhalla Friends association was formed.

OPTIMAL ACOUSTICS

Acoustic measurements confirmed an unusually low level of noise at the bottom of the quarry. The sound trial also confirmed that the high, almost vertical rock walls produced a very good reverb without a disturbing echo. With its

SFR – Final Repository for Short-lived Radioactive Waste

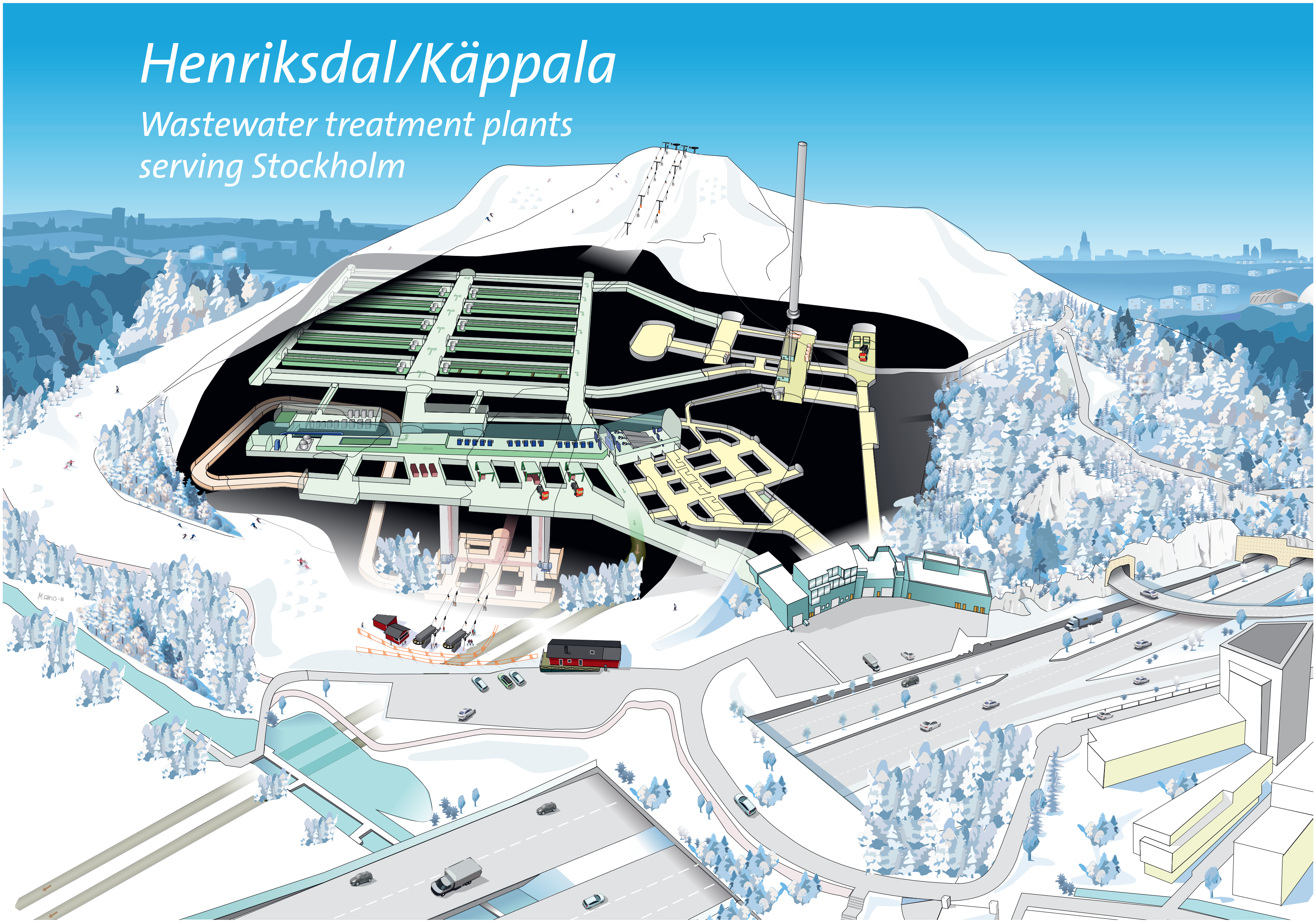
Final storage of low and intermediate level material in SKB's underground facility, SFR, located in Forsmark. An extension to the facility is planned, and is also shown in the diagram. Photo & illustration: SKB.

TIME OF CONSTRUCTION	1983-1987
PROJECT COST (SEK million)	740 (1984 value)
EXCAVATED ROCK VOLUME (m^3)	430,000
OWNER	SKB
PROJECT MANAGER	Vattenfall
MAIN DESIGNER	Vattenfall
MAIN CONTRACTOR	Vattenfall

SFR is the Swedish facility for final disposal of short-lived low and intermediate level radioactive waste. Most of the waste comes from the Swedish nuclear power plants, but also from hospitals, research institutes and industry. The facility is situated some 50 metres beneath the sea bed outside Forsmark.

Henriksdal/Käppala

Wastewater treatment plants serving Stockholm



TIME OF CONSTRUCTION	(1) 1936-1941
(2) Extended to double capacity 1953	
(3) Extended for biological treatment and pre-treatment, Sickla facility built 1963-1970	
(4) Extension for nitrogen removal 1992-1997	
(5) Facility for external organic material, new mechanical treatment in screens and sandtraps 2008- 2011	
(6) Extended to double capacity/more stringent treatment requirements 2015-2025	
PROJECT COST (SEK million)	6.3 (original plant, completed in 1941).
EXCAVATED ROCK VOLUME (m^3)	1941, approx. 90,000 ; 2015, approx. 1,500.000
OWNER	Stockholm Vatten och Avfall, the City of Stockholm (98%) and Huddinge municipality (2%).

The planned underground facility for pre-treatment of wastewater from the southern suburbs and Bromma located under the Hammarbybacken ski slope in Sickla. From here, the wastewater is diverted via two large tunnels to the Henriksdal facility for further treatment. Picture: Mario Salutskij, Illustrerad Teknik AB.

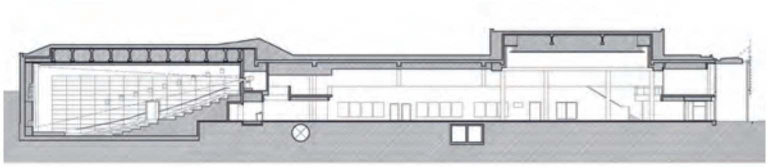
Filmstaden Bergakungen

Modern cinema complex built in rock in central Gothenburg

Photo: Bert Leandersson.

TIME OF CONSTRUCTION	Dec 2004-Nov 2006
PROJECT COST (SEK million)	250
EXCAVATED ROCK VOLUME (m^3)	10,000
OWNER	SF Bio AB
PROJECT MANAGER	EBAB i Göteborg AB
MAIN DESIGNER	Cullberg Arkitektkontor AB, PI i Göteborg AB, Bengt Dahlgren AB, WSP (formerly Gekab), Rejlers, Landskapsgruppen
MAIN CONTRACTOR	EBAB i Göteborg AB, Blasting: PEAB

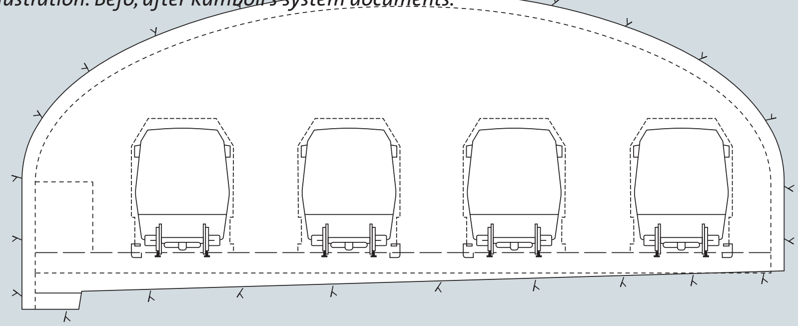
A large cinema complex has been built in central Gothenburg with little impact on the existing urban environment. Space was limited above ground, so the solution was to blast a large cut in the side of a hill and lower the structure into it.



Cullberg Arkitektkontor AB.

Norsborg Metro Depot

Prize-winning rock facility increases peak hour metro capacity



The 450-m long rock cavern can accommodate 17 trains. Illustration: Befo, after Ramböll's system documents.

Metro tracks leading into one of the three rock caverns. Photo: Skanska.

TIME OF CONSTRUCTION	2013-2016
PROJECT COST (SEK million)	2000
EXCAVATED ROCK VOLUME (m^3)	320,000
OWNER	SL (the Stockholm public transport company)
PROJECT MANAGER	Stockholm Public Transport Administration
MAIN DESIGNER	Ramböll
MAIN CONTRACTOR	Skanska and NCC

The Stockholm metro system is being upgraded, and one of the projects involves the construction of a new depot for trains at Norsborg. Limited space above ground lay behind the decision to build most of the depot in rock caverns. The depot is one of the largest of its kind in northern Europe, and the project was awarded the prize of 'Outstanding Project of the Year 2015' by the International Tunnelling and Underground Space Association (ITA).

City Tunnel

Improved rail access to central Malmö and Öresund Bridge

Photo: Sweco

TIME OF CONSTRUCTION	2005-2010
PROJECT COST (SEK million)	approx. 8600
EXCAVATED ROCK VOLUME (m^3)	600,000
OWNER	Swedish Transport Administration
PROJECT MANAGER	City Tunnel Project
MAIN DESIGNER	Sweco - COWI JV
MAIN CONTRACTOR	Malmö Citytunnel Group

Malmö Central Station was a terminus with all the associated problems. There was also a need to increase capacity in the regional rail network, improve access to the commercial centre of the city, and create a more direct link to the Öresund Bridge and Copenhagen. The solution was to build an underground section to the existing Central Station and a tunnel under the centre of the city, with two new underground stations.

Pionen

Nuclear bunker transformed into futuristic data centre

A conference room hovers under the roof of the server hall. Photo: Bahnhof.

Entrance to Pionen. Photo: Bahnhof.

A former nuclear bunker under the Vita Bergen park in Södermalm in Stockholm has been converted into a state-of-the-art data centre. The organic design in the rock cavern has attracted the attention of both architects and film producers.

Pionen server hall, with the raised conference room. Photo: Bahnhof.

Hornsberg

Energy storage facility provides free cooling

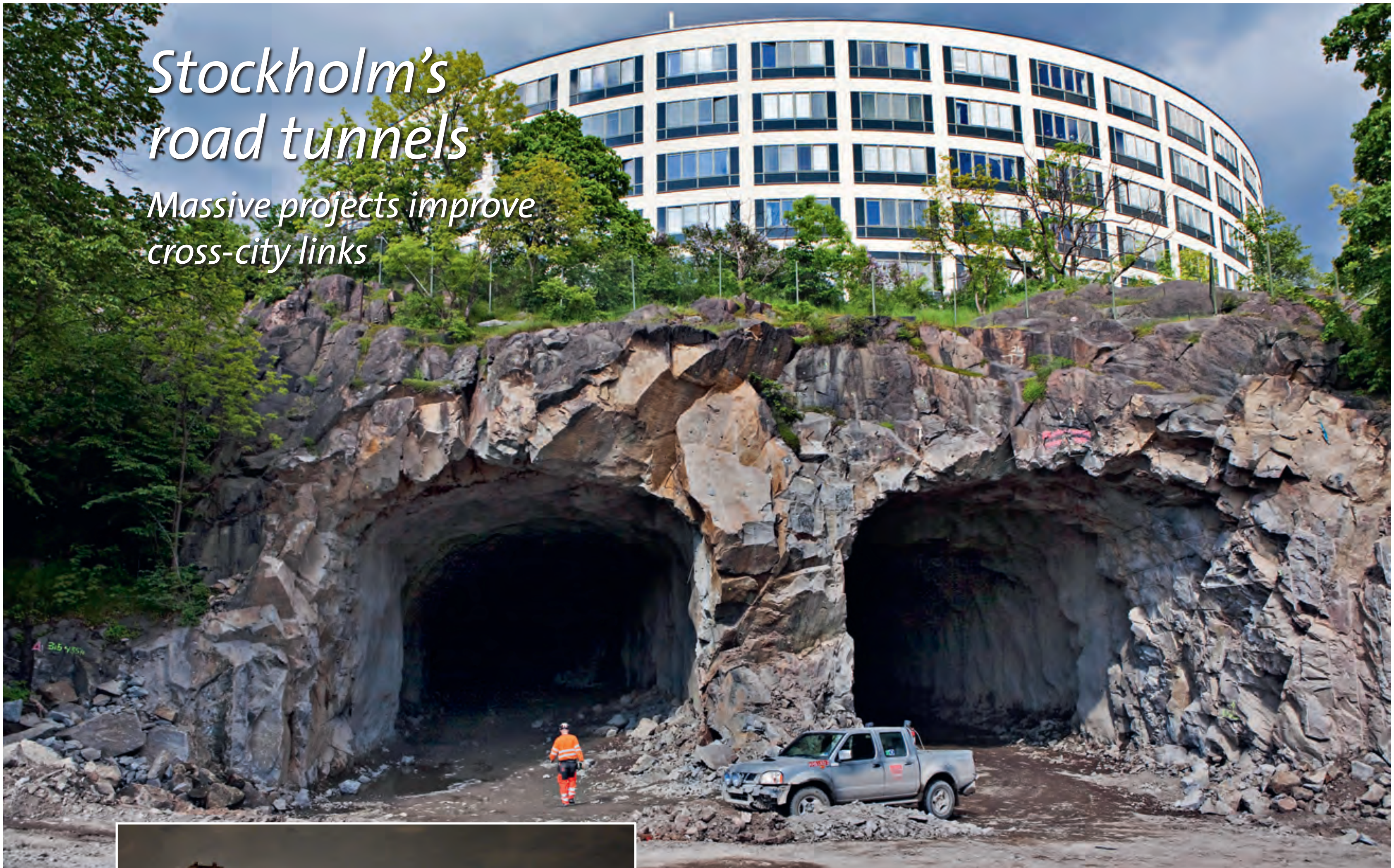
Excavation of the cooling water storage cavern. Photo: Skanska.

TIME OF CONSTRUCTION	2007-2012
PROJECT COST (SEK million)	115
EXCAVATED ROCK VOLUME (m^3)	70,000
OWNER	Fortum
PROJECT MANAGER	Termoekonomi
MAIN PLANNING	Sweco
MAIN CONTRACTOR	Skanska

District cooling is a large-scale closed circuit of cooling water used primarily in urban areas in air conditioning systems and cold storage rooms. If there is access to deep water, where the temperature is approximately 4°C, this can be used as a free input to the system. In a rock cavern at Hornsberg on the island of Kungsholmen in Stockholm, the cold water storage evens out diurnal variations in demand for cooling in properties in the city centre.

Stockholm's road tunnels

Massive projects improve cross-city links



Tunnel entrances near the Roslagstull junction. Photo: Swedish Transport Administration. Photographer. Mikael Ullén.

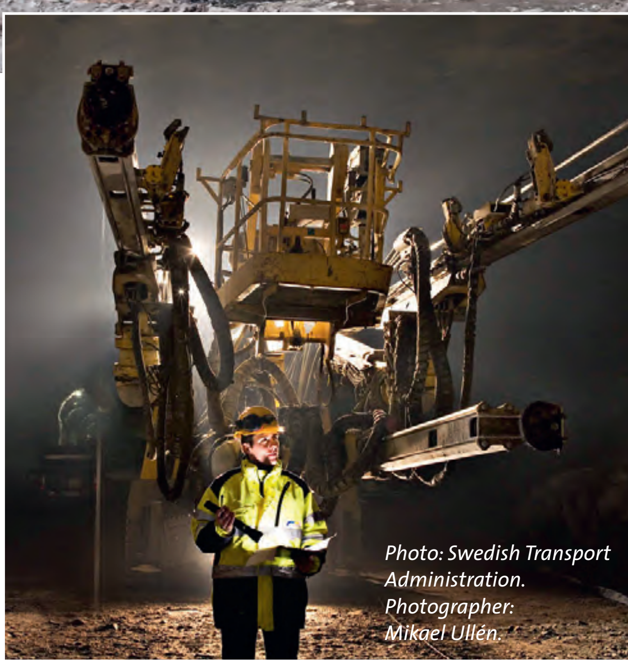


Photo: Swedish Transport Administration. Photographer: Mikael Ullén.

Urban motorways, placed mainly in tunnels, are being built around Stockholm to improve accessibility in the region. Road tunnels allow new neighbourhoods to be built, free the inner city from unwanted traffic, and increase reliability and safety in the regional transport network.

Boliden Rönnskär

Underground repository for process waste

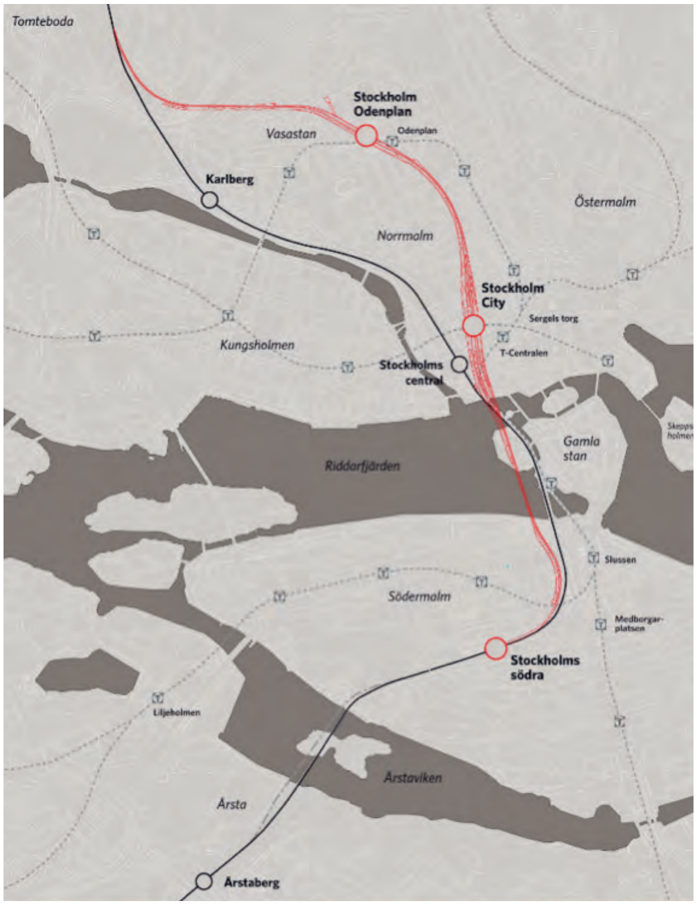
Boliden's Rönnskär copper smelter. Photo: Boliden.

TIME OF CONSTRUCTION	April 2015 to October 2017
PROJECT COST (SEK million)	600
EXCAVATED ROCK VOLUME (m^3)	275,000
OWNER	Boliden
PROJECT MANAGER	Boliden
MAIN DESIGNER	WSP Sverige AB
MAIN CONTRACTOR	STRABAG Sverige AB

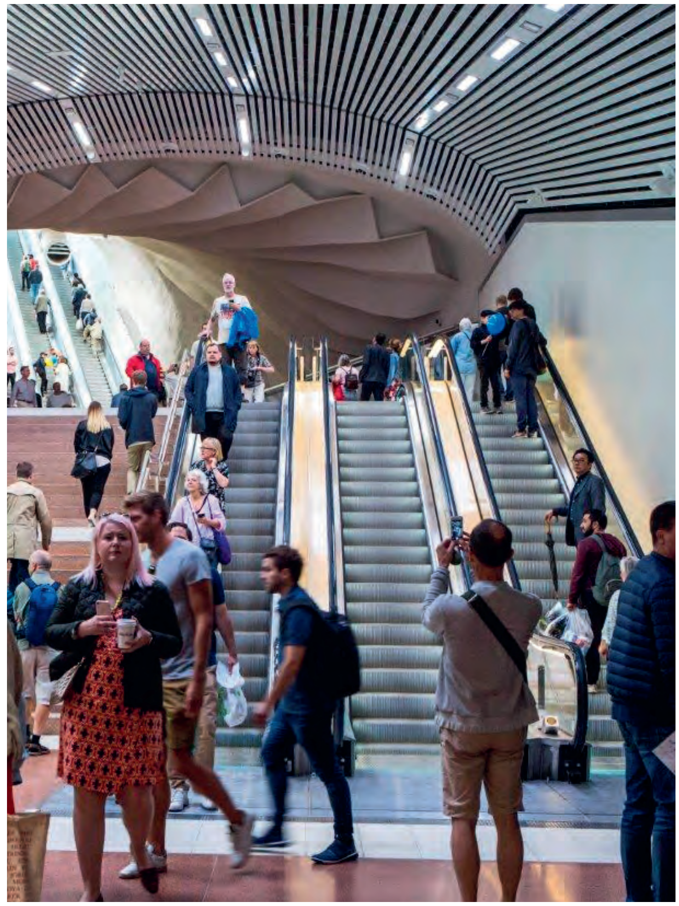
Boliden's major investment in a pioneering rock engineering project will solve the problem of hazardous process waste generated at its Rönnskär copper smelter. Management of this type of waste is an important environmental issue and has been the subject of investigation for many years. The solution is to seal the waste in rock caverns deep in the rock under the facility, making Rönnskär the first smelter in the world with a deep rock repository directly beneath the plant.

Stockholm City Line

Improved commuter access to the city centre



The route of the City Line through central Stockholm. Illustration: ©Swedish Transport Administration/City Line Project.



Escalator and stairs down to platform. Photo: ©Swedish Transport Administration/City Line Project. Photographer: Mikael Ullén

TIME OF CONSTRUCTION	2009-2017
PROJECT COST (SEK million)	16,800 (2007 price level)
EXCAVATED ROCK VOLUME (m^3)	Approx. 1.5 million
OWNER	Swedish Transport Administration
PROJECT MANAGER	Swedish Transport Administration

Congestion in the railway system through Stockholm was reaching a critical level. The solution was to build a new line, the City Line, for commuter trains, placed in tunnels under the city centre. Two centrally located underground stations are included in this extensive project.

Many artists have been involved in decorating the stations on the City Line. Here, 'Moaritisk absorbent' by Mikael Pauli, which also serves as a sound absorbent. Photo: ©Swedish Transport Administration/City Line Project. Photographer: Mikael Ullén.

Classification of underground facilities presented in Chapter 4

CULTURE & LEISURE

Aeroseum – museum in former aircraft hangar

Bergakungen – cinema complex

The Skeppsholmen Caverns – museum in former naval facility

Dalhalla – concert venue in former quarry

National Library of Sweden – book storage

Zinkgruvan – mining museum

ROADS

Göta Tunnel

Stigbergsgaraget

Southern Link – Northern Link – Stockholm Bypass

Slussen – bus terminal

RAILWAYS

Arlanda Airport stations

City Line, Stockholm

City Tunnel, Malmö

Hallandsås Tunnel

Norrland Lines

Norsborg Metro Depot

West Link, including Korsvägen station

WASTEWATER TREATMENT

Henriksdal and Käppala

Combined sewer overflow reservoir

Årsta underground holding reservoirs

ENERGY STORAGE

Hornsberg cooling storage

IKEA Uppsala, thermal energy and cooling storage

Skallen natural gas storage

HAZARDOUS WASTE STORAGE

Boliden Mineral waste storage

Underground repositories for nuclear waste

MISCELLANEOUS FACILITIES

Pionen server hall

Johannes emergency and rescue centre

Kvarntorp logistics centre and test facility

LKAB – offices and workshops at 1365-m level

Södersjukhuset Hospital technical supply system

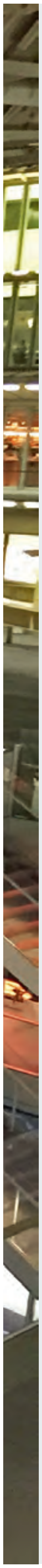
RESEARCH, TECHNICAL DEVELOPMENT AND INNOVATION

Engineering research traditionally revolves around design, materials and manufacture, and this also applies to rock engineering and mining. Various drivers lie behind the research conducted in recent decades. RTDI – research, technical development and innovation – is carried out at universities, research institutes and laboratories, including the flagship facility in Sweden, the Äspö Hard Rock Laboratory. Investigation methods, construction technology and maintenance are examples of specialisations at leading technical universities in Sweden.

Investigations of excavation-damaged zone in tunnel floor at Äspö HRL. Comparison of hydraulic conditions after blasting and wire cutting respectively. Photos: SKB and Rickard Enér.

Looking to the future

Forum Les Halles in central Paris.
Shops and offices have been built underground, creating space for green areas and a park on the surface. The complex is integrated with the underground part of RER, the commuter train system, and the metro. In the background is part of the illuminated façade of the 17th century church, St Eustache.
Photo: Per Tengborg.



This chapter considers what lies ahead. Several projects are described that have yet to proceed beyond the proposal stage – some may be built soon, while others are more futuristic. They have been chosen to reflect the enormous range in scope of underground projects, from an underground repository for nuclear waste to a small swimming pool in a rock cavern, and from an aquarium to a strategic international connection.

Climate change, resource use, and the need for sustainability will increasingly impact our societies, and no sector will remain untouched. Like the construction sector in general, rock engineering leaves a sizeable carbon footprint, and this must, and will, change in the future with improved materials and methods and other technical advances.

International research and testbed centre at Äspö

Äspö Research Village above the Äspö HRL, comprising offices, laboratories and workshops. Photo: Curt-Robert

The owner SKB will be considerably reducing its research activities at the Äspö Hard Rock Laboratory during the 2020s. Discussions are under way with potential stakeholders about converting the facility into an international centre for geoscientific research and development.

Research and development in the rock engineering field requires testing and demonstration of new ideas under realistic conditions. Traditionally, testing has been carried out during construction of new underground facilities, but constraints such as shortage of time, lack of accessibility, and a difficult work environment have often limited the possibilities to successfully carry out tests or demonstrations.

An idea currently under investigation is to set up a permanent research facility in the Äspö Hard Rock Laboratory near Oskarshamn (see Chapter 5) when SKB winds down its activities there in the 2020s.

NEW USES FOR EXISTING FACILITY

SKB has started discussions with potential stakeholders (universities, research institutes and private companies) about the possibilities of converting the laboratory into an international facility for geoscientific research, technical development, demonstrations, and practical training under realistic conditions.

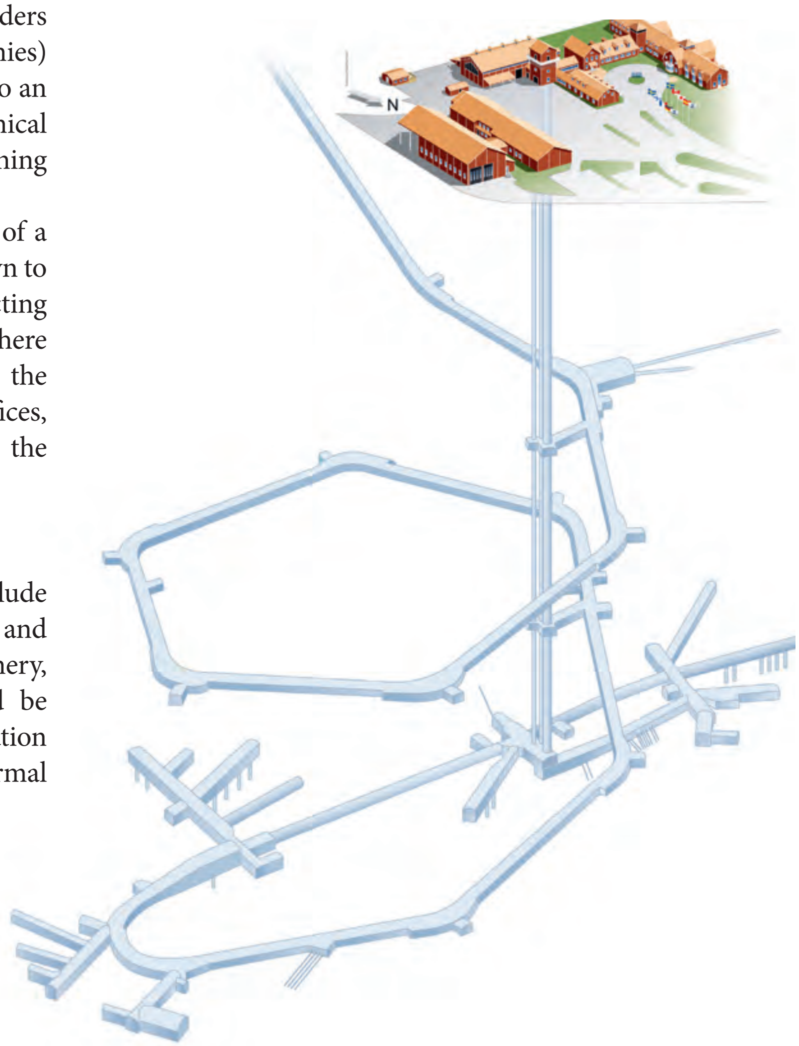
The underground part of the laboratory consists of a 3600-metre tunnel, descending in two spiral turns down to a depth of 460 metres. Along the main tunnel are connecting tunnels and niches, totalling some five kilometres, where experiments and tests could be conducted. From the surface buildings, Äspö Research Village with its offices, laboratories and workshops, an elevator connects to the underground tunnel system.

POTENTIAL ACTIVITIES

Potential research and development projects could include testing of new grouting systems, bolt reinforcement and shotcrete application methods. New types of machinery, such as automated rock excavation systems, could be demonstrated. Continual development of investigation methods for rock mechanics, hydrogeology and geothermal issues could find a natural home in the facility.

In academic circles, plans are well advanced to create a cooperative organisation for in-situ studies and testbed activities with Äspö Hard Rock Laboratory as a base. This will be designed with an open research infrastructure, where researchers from Sweden and other countries will be able to carry out individual projects.

Some companies have already invested in their own research and test facilities. For example, the machine manufacturer Epiroc has long had its own test facility in Stockholm. However, new uses for the Äspö Laboratory facilities could provide an important supplement that would benefit both research and industry.



Artist's view of the Äspö underground facility. To date, most research has taken place 460 m below the surface, but there are many suitable locations for R&D along the 3.6 km spiral-shaped tunnel down to the lowest level. See Chapter 5. Illustration: Jan Rojmar.

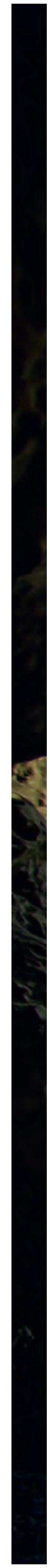
Where do we go from here?

The future undoubtedly holds major challenges, including climate change and a need to improve the way we use resources, and we must ensure sustainability.

Growing urbanisation is a global trend, and this brings a challenge – how to meet societal needs in crowded city centres. Using the underground space can be part of the solution, helping us attain the goals and fulfil requirements relating to land use planning. Sustainability also involves social aspects. Underground spaces built for people to use or work in must be made attractive and generate a positive experience. Here, planners, architects and other professionals can help create new standards.

An important objective in the immediate future is to reduce the carbon footprint, the main driver of climate change. Environmental impact will be given greater attention in all phases of an underground construction project, from the feasibility and design phases to operation and maintenance. Equipment, materials and methods with less environmental impact will be developed, such as electric machines and unmanned, remote-controlled systems.

Rock engineering will continue to deliver considerable benefits to society. Moving facilities underground will free up land for other purposes on the surface and will enable improvements in infrastructure. While doing so, the sector will continue to play its part in the work to secure our sustainable future.



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